PLASMA FILLED DIODE EXPERIMENTS ON GAMBLE II*

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Abstract

Plasma filled diode (PFD) experiments are performed on the Gamble II generator (1.5 MV, 2Ω, 60 ns pulse width), emphasizing measurements and modeling to improve the fundamental understanding of PFDs. The PFD is initially a short circuit, then opens and develops a finite impedance. The maximum impedance depends on the initial density, and generally decreases as the initial density increases. For relatively high initial plasma density (> 10^{14} cm^{-3}), the impedance is low (0.1-0.3 Ω) for most of the pulse duration. In 1D and 2D PIC code simulations, the PFD begins to open when electrode sheaths expand from both electrodes and meet in the center of the electrode gap. The cathode sheath then quickly expands to the anode, resulting in vacuum electron flow typical of a standard electron-beam diode. A simple analytic model based on the PIC code results reproduces the measured conduction-time dependence on density.

Introduction

Plasma filled diodes are used in pulsed power devices for several applications, including: eliminating the high impedance phase of vacuum diodes, improving coupling to the generator, improving power flow through vacuum convolutes, and improving coupling to a plasma opening switch (POS). The goal of the present work is to extend the physics understanding of PFDs, using a combination of experimental measurements and both numerical and analytic theory.

Previous experiments at the Naval Research Laboratory (NRL) investigated a variety of PFD properties. A Penning discharge was used to generate an *in situ* plasma in Gamble I and Gamble II experiments.[1] Flashboard plasma sources were used to inject plasma into the anode-cathode (AK) gap on Gamble II[2] and Hawk[3]. Analysis of these experiments was hampered by a lack of detailed measurements of the plasma. The present work used a gas-gun plasma source with *in situ* measurement of the plasma density. These measurements were used as inputs to particle-in-cell (PIC) codes to predict the behavior of the PFD as a circuit element, and to describe the physical processes that are responsible for the conduction and opening phases.

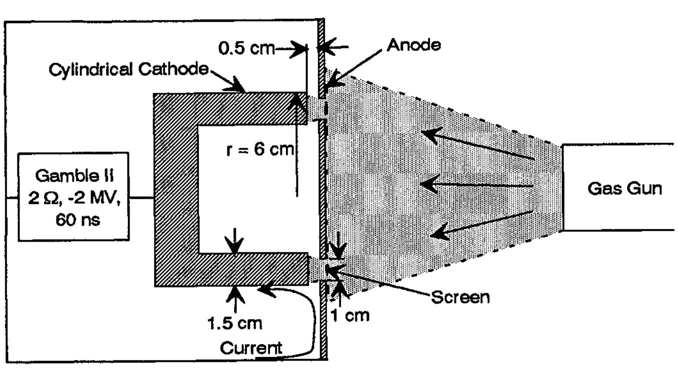

Figure 1. PFD setup on Gamble II.

Gamble II Experiments

The experimental setup for PFD experiments on Gamble II is illustrated in Fig. 1. The PFD plasma source is a coaxial gas gun, similar to the sources used for POS work in ref. [4]. The work reported here used He gas at 60 psig. The gas is introduced into the coaxial gun region by actuating an automotive fuel injector valve[5]. A capacitor (3.6 μF, 25 kV) is discharged through the gas generating a plasma that flows with a drift velocity of 5-10 cm/μs. The plasma flows through a 1-cm-wide annular slot in the anode of the PFD covered with 70%-transparent screen,. The slot is opposite the 1.5-cm-thick, 6-cm outer radius cylindrical cathode.

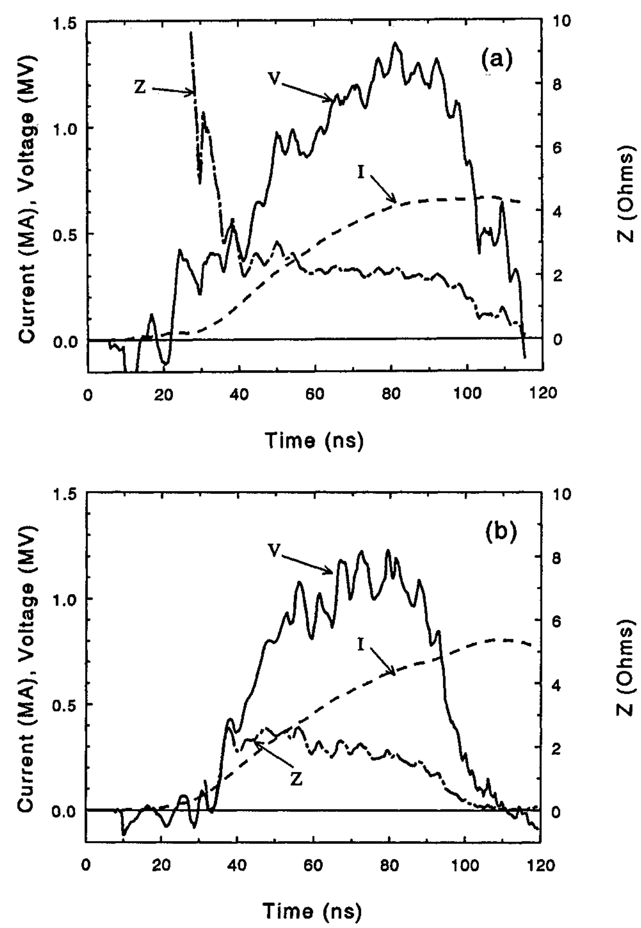

Figure 2. Electrical characteristics of (a) a vacuum diode and (b) a plasma-filled diode.

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Plasma filled diode (PFD) experiments are performed on the Gamble II generator (1.5 MV, 2Q, 60 ns pulse width), emphasizing measurements and modeling to improve the fundamental understanding of PFDs. The PFD is initially a short circuit, then opens and develops a finite impedance. The maximum impedance depends on the initial density, and generally decreases as the initial density increases. For relatively high initial plasma density (> 1014 cm-3), the impedance is low (0.1-0. 3 Q) for most of the pulse duration. In 1 D and 2D PIC code simulations, the PFD begins to open when electrode sheaths expand from both electrodes and meet in the center of the electrode gap. The cathode sheath then quickly expands to the anode, resulting in vacuum electron flow typical of a standard electron-beam diode. A simple analytic model based on the PIC code results reproduces the measured conduction-time dependence on density.

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Measurements of the plasma density are made using a CO_2 laser interferometer with the line of sight along a diameter in the middle of the 0.5-cm AK gap. Density measurements indicate that the plasma distribution is azimuthally symmetric (within about 10%) and radially confined to the 1-cm-wide slot region. Knowing the plasma density and approximate distribution, and assuming the ion specie is primarily He^+, make this experiment highly amenable to numerical modeling.

The diode is connected to the Gamble II generator (1.5 TW, 2 Ω, 60 ns) operating in negative polarity. Electrical waveforms for the case of a vacuum diode (no injected plasma) are shown in Fig. 2a. The initial load impedance is high, then falls to about 2 Ω for 60-ns, and eventually the diode shorts out when electrode plasmas from both electrodes close the AK gap (at 2-3 cm/μs). For comparison, the same waveforms are shown in Fig. 2b for a PFD. Here, the initial impedance is low while the plasma shorts out the diode AK gap. After conducting for about 20 ns, the PFD opens to the expected vacuum impedance of 2 Ω, and eventually shorts out as did the vacuum diode.

The injected plasma density was varied by changing the relative timing between firing the gas gun and Gamble II. The plasma density measured in a separate vacuum chamber (averaged over the 2-cm laser path length) is plotted in Fig. 3. The symbols indicate timings for Gamble II shots. The error bars indicate the extreme values measured for a number of gun pulses. The effect of varying the plasma density on Gamble II shots is shown in Fig. 4. The diode impedance is plotted for different (assumed) densities, corresponding to the

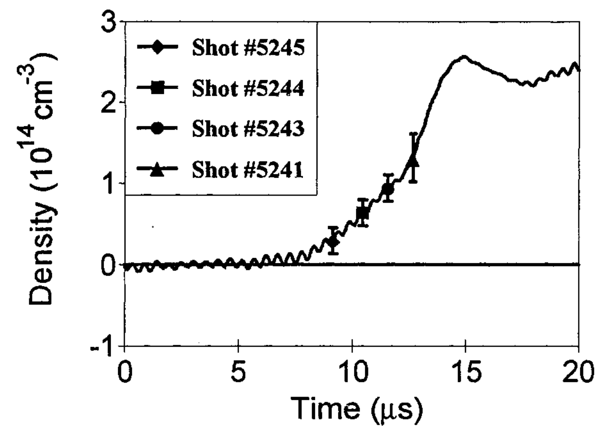

Figure 3. Density measured in PFD setup in a separate vacuum chamber using a CO_2 laser interferometer.

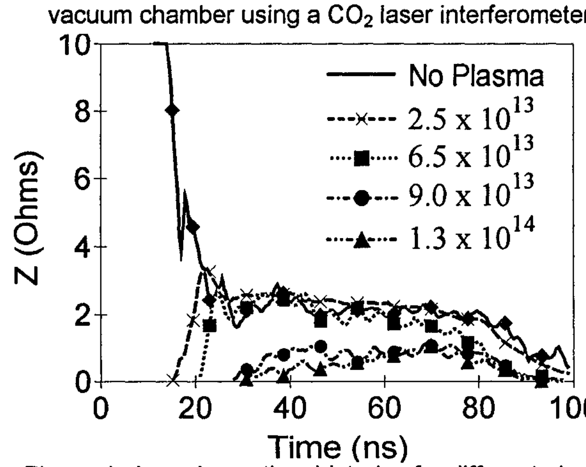

Figure 4. Impedance time histories for different plasma densities.

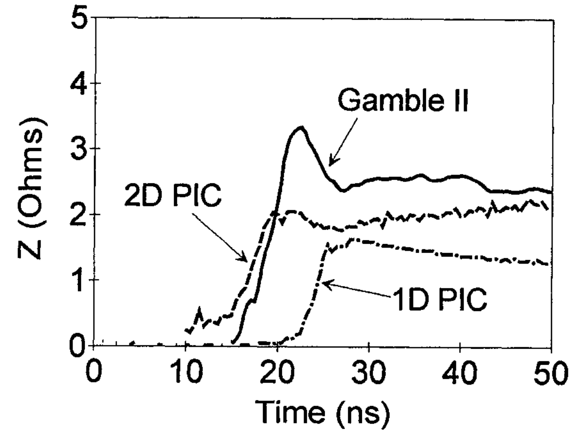

Figure 5. Comparison of impedance time histories for PIC code simulations and experiment.

symbols in Fig. 3. The vacuum diode impedance (Fig. 2a) is included for comparison. As the density increases, the conduction time increases, and the impedance decreases. At the higher densities (~ 10^{14} cm^{-3}) the impedance is much smaller than expected from the electrode spacing. This low impedance phase persists for the same time duration as the vacuum diode case. This impedance lifetime is longer than could be obtained by decreasing the vacuum gap, suggesting the PFD may be able to couple efficiently to low impedance generators without premature gap closure (for a given radius diode).

PIC Code Simulations

The Gamble II PFD experiments are simulated using 1D and 2D PIC codes. The simulations use the Gamble II configuration (Fig. 1), and assume a He^+ plasma uniformly distributed in the AK gap. The 1D simulation[6] allows variations in the axial direction only, therefore ignoring magnetic effects. A simplified description of the complicated dynamics in Ref. 6 will be given here for physical insight. Early in time, symmetric sheaths form at both electrodes and the plasma floats to a relatively high positive potential (much greater than the voltage across the AK gap). Ions leave the gap region by falling down the potential hill, further increasing the sheath size. As the diode current increases, the sheaths grow toward the center of the gap. When the sheaths meet in the center of the gap, the diode voltage starts to increase and the symmetry of the sheaths is broken. Eventually, much of the initial plasma leaves the gap and the diode voltage is dropped in a cathode sheath.

Two dimensional simulations[7] were performed to investigate (primarily) the effects of self-magnetic fields. For the Gamble II parameters, radial ion motion was found to be negligible. The electron motion in the sheaths is two-dimensional, resulting in increased ion current that effectively increases the sheath expansion rate compared with the 1D simulations. This decreases the conduction time and should result in faster opening.

PFD impedances from 1D and 2D PIC simulations of a particular Gamble II shot are compared with the measured impedance in Fig. 5. The impedance rise rate, dZ/dt, obtained from the simulations agrees with the measured value. The 2D simulation is a better match to the measured conduction time and maximum impedance, possibly because of the realistic inclusion of 2D electron flows.

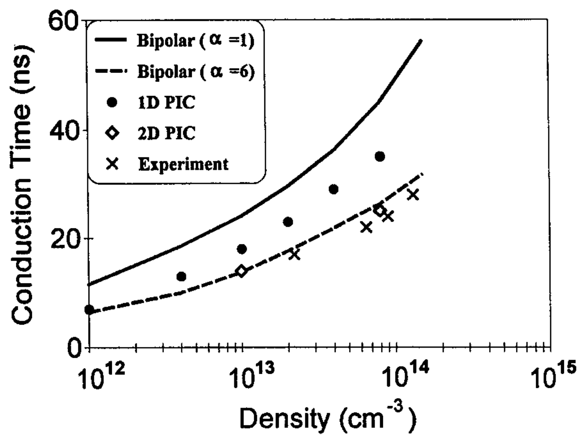

Figure 6. PFD conduction times as a function of density for experiments, PIC code simulations, and analytic models.

One experimental observation the simulations do not explain is the lower impedance measured with high density (see Fig. 4). This may be the result of a dense plasma that expands from the cathode while the PFD plasma recedes by erosion, effectively maintaining a small vacuum gap for the pulse duration.

Comparison of Theory and Experiment

The PIC simulations suggest that the conduction and opening phases of the PFD are dominated by sheath formation, basically an electrostatic process that can be enhanced by 2D electron flow. A simple analytic sheath-growth equation, which assumes the gap grows by an erosion mechanism, is given below :

$$\frac{dD}{dt} \approx \frac{J_i}{n_e e} = \frac{\alpha J_{BP}}{n_e e} ,$$

where D is the sheath size, J_i is the ion current density, n_e is the electron density, e is the proton charge, and α is a factor relating the ion current density to the bipolar value, J_{BP}. Opening is assumed to begin when the sheath size is half the AK gap.

The measured conduction times for the PFD shots in Fig. 4 are compared with the PIC and analytic estimates in Fig. 6. The simple erosion formula above matches the data assuming an ion current enhancement factor $\alpha = 6$. (For He^+, this implies the ion current is about 6% of the total current instead of 1% without enhancement.) As mentioned before, the 2D simulations are a good match to the measured conduction time.

Conclusions

A new type of PFD has been fielded on Gamble II using a gas-gun plasma source to inject a well-characterized ion specie and density into the diode AK gap, a configuration that is highly amenable to numerical simulation. For densities of 10^{13} - 10^{14} cm^{-3}, the conduction times are 10-30 ns. For low density, the PFD opens quickly to the vacuum impedance, about 2 Ω. For high density the impedance after opening is low (<< 2 Ω) but has the same time duration as a vacuum diode. PIC code simulations show the strong influence of electrostatic sheath formation during conduction and opening. Two dimensional electron motion results in faster sheath growth than for the 1D case, reducing the conduction time to values close to those obtained in experiments. A simple erosion model for the sheath growth matches the conduction time in experiments over an order of magnitude in density. The low impedance results are not explained by simulations, probably because high density plasmas expand into the AK gap from the cathode, decreasing the effective gap size. Future work will concentrate on measurements to investigate the sheath formation and gap dynamics in this PFD configuration.

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